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Growth Parameters, Yield and Grain Quality of Different Winter Wheat Cultivars Using Strip Tillage in Relation to the Intensity of Post-Harvest Soil Cultivation

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Abstract: The research has been undertaken to determine whether it is worthwhile to do a post-tillage on stubble before applying strip-till or whether tillage operations such as tillage and stubble ploughing should be performed. Therefore, ploughed tillage + strip tillage (PT), stubble discing + strip tillage (SD) and strip tillage (ST) operations were evaluated on three genetically distant winter wheat cultivars, including Formacja, Metronom and Desamo. A three-year field experiment was conducted from 2018 to 2021 at the Agricultural Experimental Station Kepa-Osiny in Pulawy, Poland. The experiment design was a split-block design with four repetitions of every treatment. The results showed that the cultivars differed in dry matter growth. However, no differences were found between the cultivar and post-harvest tillage method in terms of dry matter, plant height, and flag leaf area. Grain yield per ear was the main factor of yield variation across the cultivar and tillage systems. The extent of tillage only in the case of previously performed ploughing had an effect on the thousand grain weight. On the other hand, the omission of post-harvest tillage (ST) had a positive effect on the sedimentation index value. In terms of wheat grain yield, plough tillage (PT) proved to be the most advantageous, while reducing the intensity of tillage caused a systematic decrease in yield by 6% in the SD treatment and 9% in the ST treatment, respectively. Other quality parameters (gluten quantity, gluten index, falling number) did not depend on the applied tillage range. The response of cultivars to the applied cultivation methods was generally similar. Due to the beneficial effect of reducing the scope of cultivation on the environment, a small reduction in yield and no negative impact on the quality characteristics of grain, it is recommended to use strip-till cultivation without prior post-harvest cultivation. The results provide new insights into the growth of different winter wheat cultivars and the postharvest tillage applied, and they can be used in the future to validate existing wheat growth models.

Keywords: crop residue management; cultivation systems; dry plant mass; plant growth; yield structure; plant development

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1. Introduction

Wheat is one of the most important cereal crops grown worldwide [1]. The global wheat sown area is around 214.3 million hectares. The European Union (EU) accounts for 22.9 million hectares, and Poland ranks third in terms of wheat production volume in the EU [2–4]. Due to the high popularity of the species, research is often conducted on the appropriate agrotechnology for this cereal. In recent years, research topics have focused on minimising the negative impact of agricultural production on the natural environment and on issues related to the potential of increasing carbon sequestration to limit the rate of climate change. This is the reason why research has concentrated in recent years towards reducing the use of plough tillage, whose role in carbon dioxide emission is very large [5].

Tillage also plays a decisive role in shaping plant growth conditions, which also directly determines the productive and economic effects obtained by the farmer. It can be implemented in the traditional manner with full ploughing, but it can also be limited to shallow cover crops or eliminated altogether (direct drilling). Simplified tillage reduces negative environmental effects and increases the potential for carbon sequestration in the arable layer, but it also carries possible negative consequences in terms of lower yield [6–10]. Conservative cultivation systems, including strip tillage with stubble leaving, also influence the retention of nutrients in the soil and improve their balance, especially sulphur, which has a positive effect on the sulphur balance and the sustainability of agricultural production in soil management [11]. Ploughless cultivation, along with leaving as much crop residue as possible, can have a positive effect on soil quality, including the content of organic matter, and thus can increase the yield in wheat cultivation [12]. A particular cultivation method with the possibility of simultaneous sowing that combines the advantages of ploughing and no-till is strip-till [13]. There are reasonable views that the use of strip-till produces the same higher yields as plough tillage or zero tillage [14]. Advantages of this method include: aeration of the soil in the rhizosphere, faster heating of the soil in the strip-till, prevention of wind erosion, and a reduction in the loss of soil clay and silt particles—responsible for the soil sorption complex. Increased carbon and nitrogen content is also a beneficial effect of strip-till [15,16]. The wider row spacing used in this cultivation method may favour an increased grain yield as a result of a more efficient photosynthetic process in the plants [17].

The scientific literature on minimising plough tillage and replacing it with simplification or direct drilling is relatively rich, but most of the work published so far has dealt with the effects of different tillage methods on crop yields and quality. However, there is a lack of works that fully describe the process of shaping the final yield by assessing plant growth during the growing season in relation to the different cultivation methods. Only some works describe the growth of the root system and the aboveground weight of winter wheat in relation to tillage [18–20]. In addition, Fu et al. [21] noted that monitoring plant growth and development in a given environment is an important way to understand phenomena occurring in the soil environment. In the case of wheat, cultivation intensity and cultivar choice have been found to have some influence [22,23]. The rate of biomass growth has a direct impact on wheat grain yield and the carbon cycle [24–28]. Thus, it can be said that the determination of temporal and spatial variability of aboveground plant weight in wheat provides basic information on plant growth, but furthermore allows estimation of potential yields in a given growing season [29–31]. Conventional methods for assessing plant growth involving sampling green plants per unit area and drying them and later assessing the dry matter yield are extremely time-and labour-intensive [26,27,32], and hence, there are not many examples of work using such methods in the world literature. Therefore, this study aimed to determine the growth parameters of winter wheat grown using the strip-till method in relation to the extent of post-harvest tillage and cultivar. The research hypothesis was that both the extent of post-harvest tillage applied and the cultivar would significantly affect the plant growth rate, which would ultimately determine the level of grain yield obtained.

2. Materials and Methods

2.1. Field Conditions and Setup of the Experiment

The research hypothesis was verified by field experiments carried out in the three growing seasons: 2018/2019, 2019/2020, 2020/2021. The experiment was located at the Agricultural Experimental Station Kępa-Osiny (51°27′ N; 22°2′ E) belonging to the Institute of Soil Science and Plant Cultivation-State Research Institute in Pulawy-Poland. The soil was classified as a Gleyic Phaeozems (according to the World Reference Base for Soil Resources). Winter wheat was used as a forecrop in each year.

The field experiment was set up in the split-block method in four replications for each treatment. Three different tillage methods were applied according to Figure 1. The depth of plough cultivation was 20 cm, of the cultivator 8–10 cm, and in strip-till cultivation in the cultivation strips 18–20 cm. The distance between two rows of plants in the cultivated strip was 12 cm and the distance between the planting strips was 36 cm. The second experimental factor featured three wheat cultivars of considerably varying origin (from different breeders). They were selected taking into account all available varietal traits, mainly the resistance to biotic and abiotic stresses. The characteristics of the selected cultivars are presented in Figure 2.

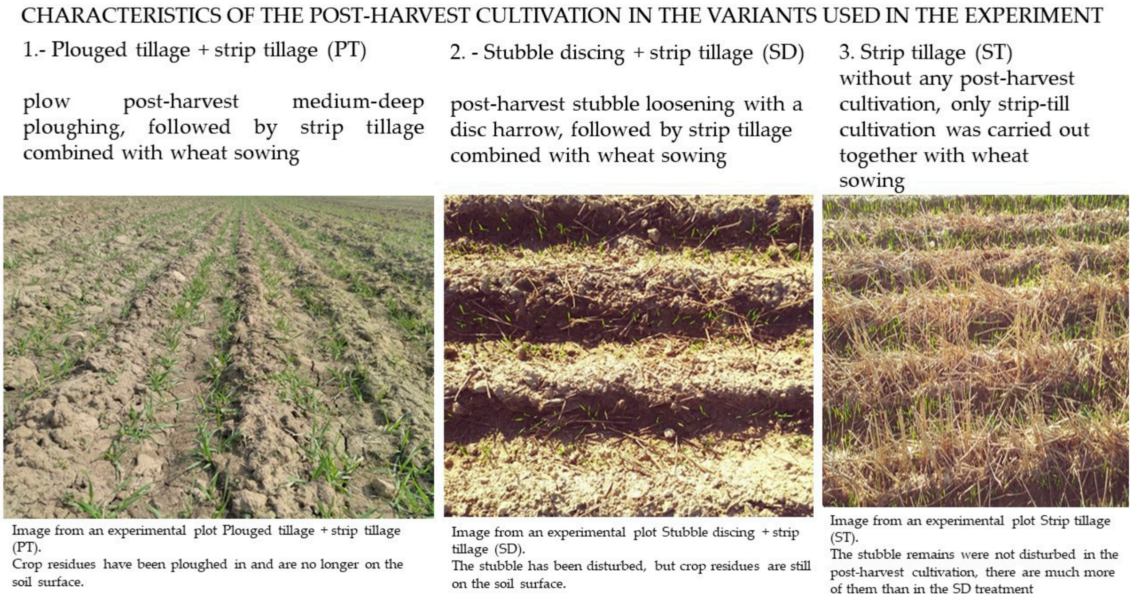

Figure 1. Characteristics of treatments using different post-harvest cultivation.

Characteristics of winter wheat varieties used in the study

FORMACJA

BREEDING COMPANY: Poznańska Hodowla Roślin
- ❖ quality variety, group A
- ❖ very high yield potential
- ❖ good resistance to fungal diseases
- ❖ good tolerance to soil acidification
- ❖ medium plants with good resistance to lodging
- ❖ good frost resistance
- ❖ exceptional tillering strength
- ❖ 1000 grain mass and high uniformity

good resistance to sprouting in the spike

METRONOM

BREEDING COMPANY: RAGT Saaten
- ❖ quality variety, group A
- ❖ good and very stable yield,
- ❖ does well in all soils and climate conditions,
- ❖ high tolerance to soil acidification allows cultivation in all locations,
- ❖ good plant health,
- ❖ good winter hardiness.

DESAMO

BREEDING COMPANY:DANKO
- ❖ quality variety, group A
- ❖ high yield potential and very high profitability of cultivation;
- ❖ useful for intensive cultivation technology on medium-quality and good soils at different sowing dates;
- ❖ good disease resistance;
- ❖ earing date – medium early;
- ❖ winter hardiness: – very good.

Figure 2. Characteristics of the cultivars used in the research.

In each year of the research, the same setup was used with a combination of different types of cultivation and cultivar. There were four replicates of every treatment. Each plot measured 9 m width and 25 m length, which corresponded to 225 m^2. The detailed setup is shown in Figure 3.

The content of nutrients and pH of soil are presented in Figure 4. The detailed agri-technical calendar is shown in Figure 5.

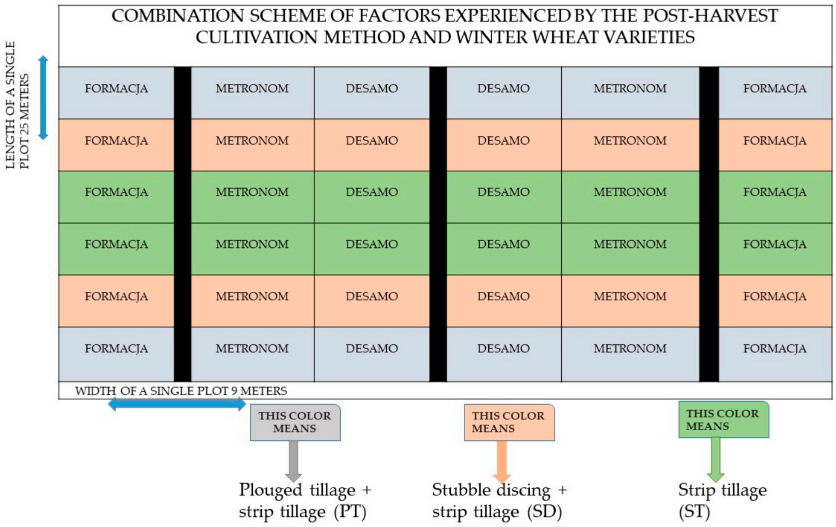

Figure 3. Plan of the applied experiment and combination of factors.

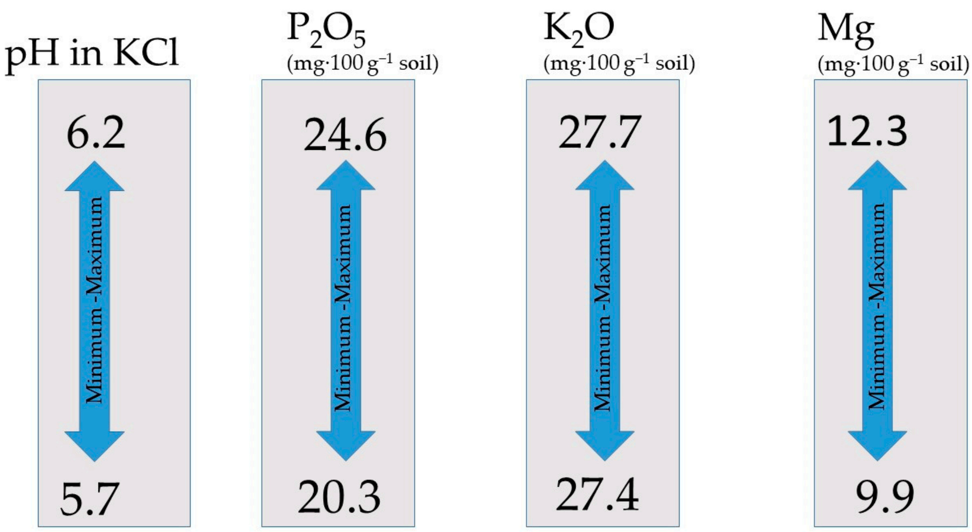

Figure 4. Characteristics of the physicochemical properties of soil.

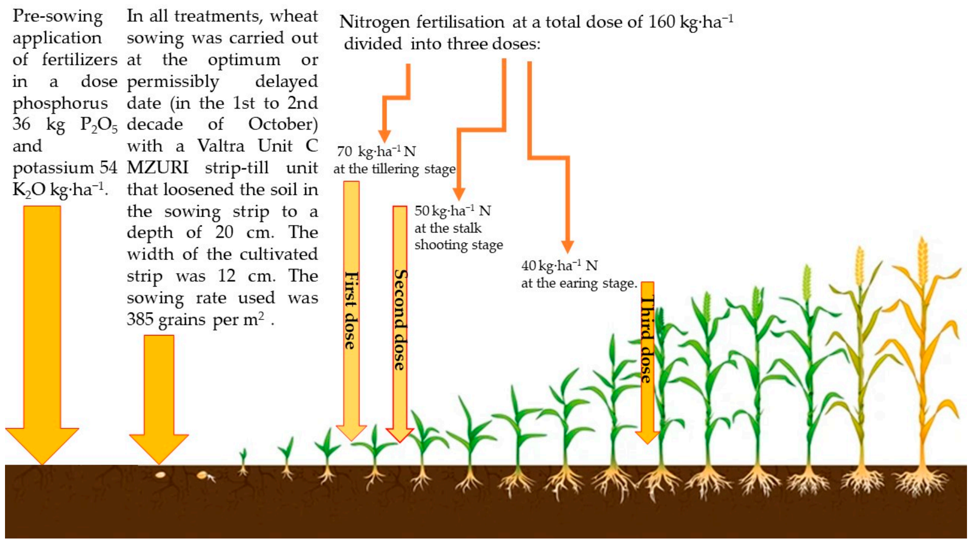

Figure 5. Agricultural technology and fertilisation used in the conducted research.

2.2. Dry Matter Yields at Selected Growth Stages

To assess adhesion parameters, plants were sampled from an area of 1 m^2, from each plot in duplicate, at the following stages

- Bush stage BBCH 29
- Stalking BBCH 32
- Flowering BBCH 59

Prior to placing the samples in the dryer, 10 plants were randomly selected from each sampled plot for measurement of height and flag leaf area, using an Area Meter AM 101 automatic leaf scanner from BioScientific LTD, Hoddesdon, UK. All green matter sampled from each plot was placed in an air-circulating dryer for 72 h, at 55 °C, and then weighed.

Meteorological conditions during the vegetation period of the plants were characterised by mean daily temperature (°C) and precipitation (mm), as well as the perennial averages of these parameters (Table 1).

Table 1. Meteorological conditions during the growing seasons in which the study was conducted.

	Temperature °C				Precipitation (mm)			
	Growing Season			Multi-Year Average	Growing Season			Multi-Year Average
Month	**2018/2019**	**2019/2020**	**2020/2021**	**1981–2010**	**2018/2019**	**2019/2020**	**2020/2021**	**1981–2010**
September	15.5	14.4	14.9	13.3	48.0	57.8	102.0	55.0
October	10.0	10.8	10.4	8.0	40.5	33.5	90.0	44.0
December	4.2	6.4	5.1	2.7	8.9	31.4	14.0	39.0
November	0.9	3.1	1.7	−1.4	61.0	47.9	19.0	37.0
January	−2.4	1.7	−1.4	−3.3	62.0	27.1	51.0	31.0
February	2.9	3.4	−2.7	−2.3	15.2	56.5	38.0	30.0
March	5.7	4.7	2.8	1.6	20.9	16.7	12.0	30.0
April	10.0	8.9	6.9	8.7	39.0	14.4	50.0	39.0
May	13.9	11.9	12.9	14.5	69.0	93.9	61.0	58.0
June	22.7	19.1	20.0	17.2	37.0	159.0	53.0	65.0
July	19.4	19.3	22.2	19.5	71.0	31.9	110.0	80.0
August	20.4	20.3	17.1	17.8	94.3	95.5	219.0	87.0

During the study, weather conditions were varied between years. Autumn and winter periods saw large differences in temperature, while meteorological conditions in the spring months were similar, not differing largely from the multi-year average. Each season saw periods with greater or lesser precipitation deficiency, but in general, precipitation totals in each season were relatively high. This was particularly the case in the third season 2020/2021, when precipitation in the preharvest was well above the multi-year average.

2.3. Yield Structure

At full maturity, plants were taken from an area of 1 m^2, two samples from each plot; thus, each treatment was represented by 8 samples in order to determine the yield components. The number of plants and the number of ears were determined in the samples. The number of grains per ear and grain weight per ear were determined in each sample on 10 randomly selected plants. The harvest index was calculated by the division of the grain yield by the sum of the grain yield and straw weight and was expressed in percentage.

Harvest was performed with a combine in the first decade of August, at the stage of full maturity. Following the harvest, grain moisture was determined at 15% moisture content.

2.4. Grain Quality

In order to determine the quality of the grain, representative samples of grain were taken after harvesting, in which the following were determined: the thousand grain weight and the bulk density of the grain (using a densimeter equipped with a 1000 mL cylinder—according to the PN-EN ISO 7971-3 standard [32]), and the quality characteristics of the flour were determined, such as: the wet gluten amount (according to standard PN-A-74042) [33], the gluten index (GI), the falling number and the Zeleny sedimentation index (according to standard PN-EN ISO 5529) [34].

2.5. Statistical Analysis of the Results

The obtained results were developed using analysis of variance (ANOVA) and the Tukey test at a significance level of $p \leq 0.05$ with STATISTICA ver. 13.1 software (StatSoft, Inc., Tulsa, OK, USA).

3. Results and Discussion

3.1. Effects of Tillage Types on Wheat Growth Parameters

Plant growth and final yield are the product of a number of processes, the most important of which is the intensity of photosynthesis, which determines the rate of growth of vegetative mass, which is essential for an adequate supply of essential assimilates to the plant during the generative phase [35]. The accumulated higher vegetative green matter of wheat increases the efficiency of sunlight utilisation, which contributes to a better use of the photosynthetic process in yield [36]. The lack of adequate green matter at any given time increases the danger of severe stress conditioning, e.g., shoot reduction and reduced ear number in wheat [37]. A fast rate of green matter growth is also important due to the higher coverage and increased competitiveness of wheat against weeds, which is also conditioned by the varietal factor [38]. It should be added that the rate of green matter accumulation is also dependent on the ability to take up nutrients from the soil with water. In the present study, the rate of green matter accumulation varied according to the cultivation method. The lowest value of this trait at the tillering stage was found in the PT plot with ploughing, while the highest was in the ST plot without post-tillage. The differences between the above-mentioned treatments exceeded 6% and were, therefore, quite large, although statistically insignificant. This indicates that the use of the plough had a negative effect on plant growth, but only in the initial period of plant development because in subsequent stages, significantly higher weight per unit area was found in the treatments with ploughing. The SD and ST treatments did not differ significantly throughout the growing season with respect to the trait in question (Table 2), so it can be concluded that the conditions for plant growth in these treatments were similar. Research by Lipiec and Nosalewicz [39] showed that the building of aboveground green matter in winter wheat depends on soil compactness and water availability. These researchers concluded that higher soil compaction has a positive effect on dry matter building in winter wheat. The results of our own research did not confirm this because it was on ploughed soil that by far the largest amount of green matter was obtained. Sha et al. [40] showed that colder and more compacted inter-row soil in strip-till cultivation was unfavourable for early root growth, resulting in limited shoot and green matter growth in maize. The fact that wheat seed sowing with a strip-till unit in ST under pre-applied ploughing conditions was slightly deeper than in the treatments with the other cultivation treatments may also have had an influence on the growth conditions associated with better water availability. Such a relationship was shown by Ali et al. [41], who found that wheat grown in furrows, where the rows into which plants were sown, gathered water and accumulated green matter better than plants grown without furrows, on a flat surface. Although, in the study described, this positive effect appeared with a delay—only at stages associated with intensive weight gain.

Table 2. Green dry matter of wheat plants (g·m^2) at different developmental stages according to cropping system, cultivar, and years of study.

Specification	Development Phase		
	Tillering	Stem Formation	Beginning of Earing
Cultivation system			
Ploughed tillage + strip tillage (PT)	97 ^{a}	434 ^{a}	1207 ^{a}
Stubble discing + strip tillage (SD)	101 ^{a}	413 $^{a\,b}$	1151 ^{b}
Strip tillage (ST)	103 ^{a}	405 ^{b}	1157 ^{b}
Cultivar			
Formacja	90 ^{b}	413 ^{b}	1181 ^{a}
Metronom	116 ^{a}	431 ^{a}	1222 ^{a}
Desamo	105 ^{b}	408 ^{b}	1112 ^{b}
Years			
2019	85 ^{b}	358 ^{c}	1329 ^{a}
2020	88 ^{b}	501 ^{a}	987 ^{c}
2021	128 ^{a}	394 ^{b}	1196 ^{b}
Factor interaction			
T	ns	*	*
C	***	ns	***
Y	***	***	***
T × C	ns	ns	**
T × Y	***	*	**
C × Y	**	***	**
T × C × Y	**	*	***

Different letters ($^{a–c}$) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, ** ≤ 0.01, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

As expected, the effect of the cultivar on plant growth rate, as measured by the amount of dry matter per unit area, was also significant. At each growth stage, the highest value for this trait was recorded in the Metronom cultivar. The cultivars Desamo and Formacja had significantly less green matter. However, there was no interaction between the cultivar and the cultivation method, indicating that despite the large variation between cultivars, their response to the cultivation method was the same. Saini et al. [42] identified cultivars that were more efficient in tolerating reduced to zero tillage among the wheat and rice cultivars tested. The reasons for the variation in the response of cultivars to cultivation conditions may be very complex. It appears that the pool of free carbohydrates may play an important role in this regard, allowing plants with a larger supply of carbohydrates to survive the stress better. The size of the root system may also play an important role here. This was pointed out by Tazhibayeva et al. [43], who showed that the development of the root system varies between cultivars and may determine more efficient water uptake under drought conditions and thus mass accumulation. This was also confirmed by results obtained by other authors [17,44–46].

Kumar and Sachan [2], as well as Wilczewski et al. [47], pointed out the large role of mulch in no-tillage in shaping soil moisture. In the studies of these authors, no-tillage and direct seeding into the mulched soil surface had a more beneficial effect on wheat yield than ploughing and irrigation. In the present study, mulch on the soil surface existed in large amounts only in the inter-rows. The strongest surface coverage of mulch (cut straw) was in the inter-rows in the ST, where the degree of soil cover was about 50%. At the SD treatment, the amount of mulch remaining on the surface was already considerably less (around 15%). It seems that the positive effect of mulch on wheat growth and yield was limited due to the relatively high rainfall during the years of the study, which meant that the reduction in water loss from the mulched surface did not have a clearly positive effect in shaping plant growth parameters. Sha et al. [48] found that strip-till plants had the ability to rapidly adapt and recover from abiotic stresses due to which green matter was comparable in strip-till and plough tillage. Our research showed that the system of applied post-harvest cultivation together with strip tillage had a significant interaction in combination with the accumulated green mass, but only in two phases—the stem formation and the beginning of earing. In the case of cultivars, a highly significant interaction (p value < 0.001) was found in the tillering and the beginning of earing phases. Years also had a significant iteration in each phase studied (p value < 0.001). Interactions between individual experimental factors were also significant. We found a non-significant interaction only between T × C in two developmental phases: tillering and stem formation. Rieger et al. [49] also showed that the cultivation system had no significant interaction with the green mass of plants, which we also noted in our own studies. Plaza-Bonilla et al. [50] also demonstrated the lack of interactions, indicating that green matter and root matter develop the same in different tillage systems.

The flag leaf is an organ that plays a very important role in shaping the assimilation process and, consequently, the yield of wheat plants. Its larger surface area promotes a higher intensity of photosynthesis-related processes [51,52]. In our study, neither the crop used, nor the cultivar had a significant effect on this trait of wheat plants (Table 3). However, a strong effect of years related to the occurrence of different weather conditions was found. As indicated by Yang et al. [53], the area of the flag leaf depends precisely on weather conditions and is smaller under stress conditions. In particular, drought stress associated with water scarcity negatively affects flag leaf area in wheat [54,55]. The lack of differences in the trait in question according to the experimental factors suggests that the magnitude of drought stress was similar in all treatments. We found a significant interaction in flag leaf area and other factors only between years (Y), and also between factors C × Y and T × C × Y.

Table 3. Flag leaf area (cm^2) according to cultivation method, cultivar and years of study.

Specification	Flag Leaf Area (cm^2)
Cultivation system	
Ploughed tillage + strip tillage (PT)	22.5 [a]
Stubble discing + strip tillage (SD)	22.7 [a]
Strip tillage (ST)	23.2 [a]
Cultivar	
Formacja	25.5 [a]
Metronom	25.3 [a]
Desamo	24.9 [a]
Years	
2019	20.1 [c]
2020	23.2 [a]
2021	21.6 [b]

Table 3. *Cont.*

Specification	Flag Leaf Area (cm^2)
Factor interaction	
T	ns
C	ns
Y	***
T × C	ns
T × Y	ns
C × Y	*
T × C × Y	*

Different letters ($^{a–c}$) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

The height of the plants at the different phases depended significantly on the cultivation method used. Wheat plants were highest at the stem formation and earing stages in the ST treatment (Table 4). Plant height, on the other hand, did not depend significantly on the cultivar, although it is worth noting the slightly higher height of the Metronom cultivar at the tillering and stem formation stages. This trend was reversed at the beginning of earing when plants of the Metronom cultivar were characterised by the lowest height compared to the other cultivars. It is a well-known fact that plants vary greatly depending on the weather conditions specific to the vegetation period. Künze et al. [56] also showed a significant effect of years on plant height than the cultivar itself. In our own research, the colder April in 2021 could have slowed down plant growth and accelerated the course of further phenological phases associated with the photoperiod, which could have resulted in a lower plant height this year compared to 2019 and 2020. The research by Wilhelm et al. [57] confirms such a relationship, which was found in our own research. All of the experimental factors, T, C and Y, showed highly significant interactions (p value < 0.001) with plant height in individual phases. We also found highly significant interactions between factors C × Y; C × Y and T × C × Y (p value < 0.001). We did not find a significant interaction only between T × C in the stem formation phase.

Table 4. Winter wheat plant height (cm) at different developmental stages according to cropping system, cultivar and years of study.

Specification	Development Phase		
	Tillering	Stem Formation	Beginning of Earing
Cultivation system			
Ploughed tillage + strip tillage (PT)	27.3 ^{a}	51.2 ^{a}	86.9 ^{b}
Stubble discing + strip tillage (SD)	26.9 ^{a}	50.6 ^{a}	86.3 ^{b}
Strip tillage (ST)	27.7 ^{a}	53.4 ^{a}	90.1 ^{a}
Cultivar			
Formacja	26.2 ^{a}	50.9 ^{a}	89.3 ^{a}
Metronom	28.6 ^{a}	52.2 ^{a}	85.4 ^{a}
Desamo	26.6 ^{a}	50.5 ^{a}	93.2 ^{a}

Table 4. *Cont.*

Specification	Development Phase		
	Tillering	**Stem Formation**	**Beginning of Earing**
		Years	
2019	27.0 [a]	50.6 [b]	91.2 [b]
2020	25.9 [a]	64.7 [a]	97.1 [a]
2021	19.0 [b]	41.1 [c]	61.2 [c]
		Factor interaction	
T	***	***	***
C	***	***	***
Y	***	***	***
T × C	*	ns	***
T × Y	***	***	***
C × Y	***	***	***
T × C × Y	***	***	***

Different letters ([a–c]) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

3.2. Effects of Tillage Types on Wheat Yield

Grain weight was significantly higher for the PT treatment compared to the SD and ST treatments (Table 5). The other two treatments showed no significant differences between them. Straw weight was also significantly higher in the PT treatment than in the SD and ST treatments, by 9.5 and 10.1%, respectively.

The varietal factor significantly differentiated wheat grain yields. Formacja showed a significantly higher grain yield than cultivar Desamo. In contrast, the cultivars showed no significant differences between each other in terms of straw weight. The harvest index value is a trait that determines the ratio between accumulated vegetative green matter and the main yield, which in the case of wheat is grain [58]. White and Wilson [59] indicate that the limiting harvest index (HI) value for wheat to guarantee the highest possible yield is 0.55. In their study, this value was slightly lower and did not depend on the cropping system and cultivar. In some studies [60], the role of cultivation system and cultivar in shaping the HI was greater than in our study. Grain mass $g \cdot m^{-2}$ showed a highly significant interaction between T and Y (p value < 0.001), and a significant interaction between C (p value ≤ 0.05). Straw mass had a highly significant interaction with Y (p value < 0.001) and a significant interaction with T (p value ≤ 0.01). In addition, there was a highly significant interaction between the factors T × Y (p value < 0.001), and a significant interaction between C × Y (p value ≤ 0.05). In the Harvest index, we also found a highly significant interaction between C and Y (p value < 0.001). We also found a high interaction between T × Y and C × Y (p value < 0.001).

The role of the tillage method in shaping cereal yields may result from its influence on plant density [61]. In the presented study, however, the range of tillage applied did not significantly affect the size of this wheat canopy trait (Table 6), although it is undoubtedly noteworthy that there was a tendency for the number of plants per unit area to decrease in the treatment with the least intensive tillage (ST). Similarly, Wesołowski and Cierpiała [62] showed a lower wheat grain yield when post-harvest tillage was reduced in winter wheat cultivation. Also, the genetic factor did not have a significant effect on this wheat canopy trait, although the tendency towards a lower value of this trait in the Formacja cultivar was quite pronounced. However, the main role in shaping grain yield, according to cultivar, was played by yield per ear, which varied a lot over the years—a generally known relationship resulting from the influence of weather conditions on this trait [63–65].

Table 5. Grain weight, straw and harvest index value according to crop, cultivar and years of study.

	Grain Weight g·m^{-2}	Straw Weight g·m^{-2}	Harvest Index (%)
	Cultivation system		
Ploughed tillage + strip tillage (PT)	970.7 [a]	953.2 [a]	0.51 [a]
Stubble discing + strip tillage (SD)	886.3 [b]	891.9 [a b]	0.50 [a]
Strip tillage (ST)	881.0 [b]	861.8 [b]	0.51 [a]
	Cultivar		
Formacja	955.0 [a]	887.4 [a]	0.52 [a]
Metronom	916.4 [a b]	890.7 [a]	0.51 [a]
Desamo	866.7 [b]	928.8 [a]	0.49 [a]
	Years		
2019	1027.0 [a]	981.4 [b]	0.52 [a]
2020	925.6 [b]	1066.4 [a]	0.47 [b]
2021	785.5 [c]	659.0 [c]	0.55 [a]
	Factor interaction		
T	***	**	ns
C	*	ns	***
Y	***	***	***
T × C	ns	ns	ns
T × Y	ns	***	***
C × Y	ns	*	***
T × C × Y	ns	ns	ns

Different letters ([a–c]) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, ** ≤ 0.01, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

In a study by Parylak and Pytlarz [66], limiting wheat pre-sowing cultivation to the use of a cultivating unit resulted in high yield decreases, compared to plough tillage, but it should be noted that the mentioned researchers used sowing by the traditional method, i.e., with a standard seed drill. Jaskulska et al. [61] achieved similar results to our study in terms of winter wheat yield depending on the tillage method. These authors also used a Mzuri unit for setting up the experiment and compared this treatment to conventional ploughing and simplified (no-plough) tillage, in which sowing was conducted with a seed drill. Similar results were also obtained by Mohammadi et al. [67]. It should be emphasised that in the strip till method, the soil in the sowing strip is cultivated to a depth of 20 cm, i.e., to a depth appropriate for ploughing and even deeper, which lowers the negative effects associated with too much soil compaction that occurs in direct sowing (sowing without prior tillage). Therefore, on the basis of the present research, it may be concluded that the strip-till method in the conditions of the clay soil, in which our research was conducted, does not create the same conditions for plant growth as with properly conducted ploughing, but the negative effects associated with its non-application are the same.

Table 6. Yield and its structure according to the crop used, cultivar and years of study.

Specification	Tillering Index	Plant Density (pcs·m^{-2})	Number of Ears (pcs·m^{-2})	Weight of Kernels per Ear (g)	Yield (t·ha^{-1})
Cultivation system					
Ploughed tillage + strip tillage (PT)	2.2 ^{a}	284 ^{a}	477 ^{a}	1.87 ^{a}	7.88 ^{a}
Stubble discing + strip tillage (SD)	1.9 ^{a}	279 ^{a}	478 ^{a}	1.63 ^{b}	7.41 ^{b}
Strip tillage (ST)	2.1 ^{a}	267 ^{a}	490 ^{a}	1.62 ^{b}	7.16 ^{b}
Cultivar					
Formacja	2.1 ^{a}	273 ^{a}	469 ^{a}	1.75 ^{a}	7.68 ^{a}
Metronom	2.1 ^{a}	278 ^{a}	488 ^{a}	1.78 ^{a}	7.53 ^{a}
Desamo	2.2 ^{a}	282 ^{a}	488 ^{a}	1.59 ^{b}	7.24 ^{b}
Years					
2019	1.6 ^{c}	310 ^{a}	505 ^{a}	1.82 ^{a}	8.10 ^{a}
2020	2.3 ^{b}	260 ^{b}	482 ^{b}	1.64 ^{b}	7.73 ^{b}
2021	2.5 ^{a}	262 ^{b}	458 ^{b}	1.66 ^{b}	6.62 ^{c}
Factor interaction					
T	ns	ns	ns	***	ns
C	ns	ns	ns	***	ns
Y	***	***	***	***	ns
T × C	ns	ns	ns	**	ns
T × Y	*	ns	*	ns	ns
C × Y	*	ns	***	ns	ns
T × C × Y	*	ns	ns	*	ns

Abbreviation 'pcs' means 'pieces'. Different letters ($^{a–c}$) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, ** ≤ 0.01, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

Among the studied yield structure traits, only for the weight of kernels per ear (g) was a highly significant interaction (p value < 0.001) term was found between T and C. We found a highly significant interaction between Y (p value < 0.001) and all yield structure traits except the grain yield itself. C × Y; C × Y; T × C × Y showed significant interaction ($p \leq 0.05$) with each other in terms of tilering index. The number of ears was influenced by the interaction between T × Y ($p \leq 0.05$) and C × Y (<0.001). The weight of kernels per ear (g) showed a significant influence between experience factors T × C (p value ≤ 0.01) and T × C × Y (p value ≤ 0.05). Roohi et al. [68] indicate that the interaction between the cultivation system and the cultivar in the yield concerns the grain head from the spike, which was confirmed in our own research. Herrera et al. [69] compared the available scientific studies and showed that the percentage of reported significant T × C interactions was higher for spring wheat (71%) than for winter wheat (40%).

3.3. Effects of Tillage Types on Wheat Grain Quality

In our own research, it was found that the cultivation method as well as the cultivar had a significant effect on the thousand grain weight (TGW). The highest value of this grain trait was found under post-harvest plough tillage (PT) and the lowest was when strip tillage was combined with sowing made in no-till (ST) (Table 7). The higher grain weight and yield in the plough system relative to the no-till system were also found by other authors [70,71], but it should be noted that they did not use a strip-till unit for sowing. The effect of the cultivar on thousand grain weight was also significant. The highest thousand grain weight was found in the Metronom cultivar and the lowest in the Desamo cultivar. An important indicator of grain quality, which determines its maturity, is its bulk density. This trait, which determines its milling value, did not significantly depend on the post-harvest tillage applied, although it should be emphasised that the tendency for a higher value of this trait in the PT treatment was clear. Among the winter wheat cultivars tested, we found a significant effect on the density of grain at the bulk state, as each cultivar differed significantly in this respect. The Formacja cultivar had the highest value for this trait, which was 4% higher than that of Metronom and 9% higher than that of Desamo. Some scientific studies have shown that the value of winter wheat grain density is higher when plough tillage is applied than under reduced tillage conditions [72]. In contrast, Jaskulska et al. [8] and Taner et al. [73] showed no effect of using the tillage system (ploughing, reduced tillage and no-till) on this grain trait. Large differences between cultivars in grain density were pointed out by many authors [74–76]. Bobryk-Mamczarz et al. [77] pointed out the influence of weather conditions varying over the years on this trait, which was also confirmed by their own research, as the grain density values obtained in each year of the study differed significantly. The tests carried out showed that the method of post-harvest cultivation had no statistically significant effect on the amount of total gluten. Only a statistically insignificant tendency towards a slightly higher amount of gluten in the grain from the ST treatment was found. The results obtained in our study are in line with what was obtained in their studies by Šíp et al. [78] and Woźniak and Rachoń [79]. In studies by other authors, the effect of applied soil tillage intensity in shaping the amount of gluten varied. Amato et al. [80] showed a higher amount of gluten in grain from treatments with more intensive (plough) cultivation, while Konavko and Ruža [81] showed the opposite relation, i.e., a higher amount of gluten in wheat grain from treatments with less intensive cultivation. Our own research showed that the amount of gluten was dependent on the winter wheat cultivar. The cultivar Desamo had the statistically significant highest amount of gluten. On average, the Metronom cultivar contained 5% less gluten and the Formacja cultivar 14% less. There is a consensus among various authors dealing with the issue of wheat grain quality that the amount of gluten is a varietal trait [82–84]. A very extensive study in this field on 762 cultivars, also confirming the mentioned relationship, was conducted by Pengpeng et al. [85]. No less important than the cultivar in shaping the amount of gluten is the variable weather conditions over the years. This is confirmed by our own research. Irrespective of cultivation method and cultivar, on average, the highest amount of gluten was found in 2020, and in the other two years, 2019 and 2021, 6.3% and 3.0% less, respectively (Table 7). The important role of years in shaping the amount of gluten was also emphasised by other authors [86,87]. This is related to the weather-dependent efficiency of nitrogen use for protein synthesis in grain [88–90]. The intensity of the post-harvest tillage applied did not significantly affect the gluten index value (Table 7). In contrast, a study by Gawęda and Haliniarz [70] showed that tillage intensity can significantly modify this trait. The authors cited found higher gluten index values under no-tillage compared to plough tillage. A different relationship—a higher gluten index under reduced tillage than under no-tillage—was found by Buczek et al. [91]. In our study, a strong influence of the varietal factor on the gluten index was shown. The Formacja cultivar had by far the highest value (81% on average) of the trait in question. In the other two cultivars, the gluten index was significantly lower. The gluten index is cultivar-related in winter wheat [92], which was also confirmed in our own research. Our own research also showed, the effect of years on the gluten index value. The lowest value of this trait was found in 2020, while the other years did not differ significantly in the value of this trait (Table 7). In general, there is some consensus in the literature on the large effect of weather condition variance over the years, with this being explained by drought stress, the occurrence of which reduces the value of this trait [93]. The sedimentation index relates to both the quality and quantity of protein in the grain, and therefore has an impact on the quality of the bread obtained and, in particular, its structure [94]. The highest possible value is desirable. A high sedimentation rate should be combined with a high content of gluten proteins, especially gluten, which is the most important for baking [95]. Our study showed a significant effect of the extent of post-harvest cultivation on the Zeleny sedimentation coefficient. Its highest value was found in the ST treatment, in which strip-tillage with seed sowing was carried out directly into the stubble. Significantly lower values for this parameter were found in the reduced tillage (SD) and plough tillage (PT) treatments, by 8 and 13%, respectively. Similar trends in the effect of tillage intensity on sedimentation rate were also found by Bilalis et al. [96] and Wozniak and Rachoń [79]. In the study of Šíp et al. [78], on the other hand, the sedimentation rate was higher with a plough tillage system than with no-tillage.

Table 7. The value of the analysed grain quality traits depending on the post-harvest cultivation used, cultivar and year of research.

Specification	Thousand Grain Weight (g)	Bulk Density of Grain ($kg \cdot hl^{-1}$)	Amount of Gluten (%)	Gluten Index (%)	Sedimentation Index Zeleny (cm^3)	Falling Number (s)
Cultivation system						
Ploughed tillage + strip tillage (PT)	39.2 ^{a}	74.3 ^{a}	33.7 ^{a}	66 ^{a}	46 ^{c}	358 ^{a}
Stubble discing + strip tillage (SD)	37.9 ^{b}	72.1 ^{a}	33.6 ^{a}	66 ^{a}	49 ^{b}	361 ^{a}
Strip tillage (ST)	36.1 ^{c}	71.9 ^{a}	34.0 ^{a}	63 ^{a}	53 ^{a}	374 ^{a}
Cultivar						
Formacja	37.9 ^{b}	76.0 ^{a}	30.9 ^{c}	81 ^{a}	47 ^{b}	365 ^{b}
Metronom	41.5 ^{a}	72.7 ^{b}	34.2 ^{b}	59 ^{b}	59 ^{a}	321 ^{c}
Desamo	33.8 ^{c}	69.5 ^{c}	35.9 ^{a}	55 ^{c}	42 ^{c}	404 ^{a}
Years						
2019	37.9 ^{a}	72.3 ^{b}	30.5 ^{c}	68 ^{a}	39 ^{c}	371 ^{a}
2020	37.8 ^{a}	69.5 ^{c}	36.8 ^{a}	62 ^{b}	60 ^{a}	363 ^{a}
2021	38.0 ^{a}	77.6 ^{a}	33.7 ^{b}	66 ^{a}	49 ^{b}	358 ^{a}
Factor interaction						
T	***	**	ns	*	***	ns
C	***	***	***	***	***	***
Y	ns	***	***	*	***	ns
T × C	**	ns	ns	***	ns	ns
T × Y	ns	ns	ns	ns	**	ns
C × Y	***	***	***	ns	***	***
T × C × Y	ns	ns	ns	*	*	ns

Different letters ($^{a–c}$) mean the significant difference ($p \leq 0.05$) according to ANOVA and Tukey's test. Significant interaction on level p value * ≤ 0.05, ** ≤ 0.01, *** < 0.001, and ns—not significant difference, T—tillage, C—cultivar, Y—year.

In our study, there was a significant effect of cultivar on the Zeleny sedimentation coefficient. The highest value was found in the Metronom cultivar, which had a higher index than the Formacja cultivar by 20% than on the Desamo cultivar by 29%. The strong influence of the cultivar on the value of the sedimentation index was indicated by many authors [79,95,97–99]. In addition, our study found a large variation in sedimentation rate values between years (Table 7), the highest being recorded in 2020, with significantly lower values in the other years. Tatar et al. [100] consider that the magnitude of the sedimentation index is conditioned by the occurrence of drought at the grain pouring stage. In the cited study, the sedimentation rate was significantly lower under rainfall deficit conditions. The falling number is considered to be an important discriminator for the technological value of the grain, which determines alpha-amylase activity. The minimum value of the falling number according to wheat standards (EN ISO 3093) is 250 [101]. In our study, the tested grain from each research treatment met this requirement. However, there was no statistically significant effect of the extent of post-harvest tillage on the falling number value. Weber [86] and Buczek et al. [91] found that plough tillage favoured a higher fall number compared to reduced tillage. On average, the highest falling number was characterised by the cultivar Desamo (independent of the treatment, more than 400), but in the case of the other two cultivars, the values of this trait were also high and exceeded 300. Similarly, a large role of the cultivar in shaping the falling number was shown by Knapowski et al. [102] and Amiri et al. [83]. In our own study, there was no significant effect of the study years on the value of falling number. However, the literature indicates that weather conditions have the greatest influence on the value of this trait. The lack of heavy rainfall in the pre-harvest period favours a high value of the fall number [103]. The tillage system showed significant interaction (p value < 0.001) between the thousand grain weight and Zeleny's sedimentation index, the bulk density of grain (p value < 0.001) and gluten index ($p \leq 0.05$). The cultivar showed a high significant interaction (p value < 0.001) with each of the tested grain quality traits. Years of research had a high significant interaction (p value < 0.001) with the bulk density of grain, amount of gluten and Zeleny's sedimentation index, and also significant interactions with the gluten index ($p \leq 0.05$). A highly significant interaction (p value < 0.001) was also confirmed between the C $\times$ Y experience factors on traits such as thousand grain weight, bulk density of grain, amount of gluten, Zeleny's sedimentation index and falling number. T $\times$ C had a significant interaction for gluten index (p value < 0.001) and thousand grain weight (p value $\leq$ 0.01). T $\times$ Y had a significant interaction for Zeleny's sedimentation index (p value $\leq$ 0.01). Interactions between T $\times$ C $\times$ Y had a significant impact (p value $\leq$ 0.05) on gluten index and Zeleny's sedimentation index. Buczek et al. [91] study of the interaction between T, C and Y showed a highly significant interaction of Zeleny's sedimentation index and falling number and gluten index only for T and C, which was also confirmed by our own study.

4. Conclusions

The lowest value of this trait at the tillering stage was found in the ploughed tillage + strip tillage treatment. In the subsequent growth phases, this was the treatment with the highest aboveground weight, indicating that the plant growth rate was clearly higher in this treatment. The genetic factor had a significant influence on plant growth rate. In each growth phase, the highest value for this trait was recorded in the Metronom cultivar. The cultivars Desamo and Formacja had a significantly lower green matter. The results of the present study can be used to validate existing wheat growth models. The extent of harvest tillage preceding the strip-till sowing of wheat had a significant effect on the thousand grain weight. The higher value of this trait was characterised by grain obtained from the treatment in which strip-tillage of wheat was applied after ploughing. The grain quality parameters (gluten content, gluten index, falling number) did not depend on the applied post-harvest tillage regime, except for the sedimentation index. The beneficial effect of strip-till cultivation on the environment and the slight decrease in yield and no effect on quality characteristics mean that we recommend the use of strip-till cultivation without prior post-harvest cultivation, but it is important to select the appropriate winter wheat cultivar.

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